# An experimental measure of the phase diagram of bulk nuclear matter

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Since the birth of the liquid drop model, over 60 years ago, nuclei have been recognized as charged drops of a van der Waals like fluid. Soon after, the concept of cold neutral, symmetric (or bulk nuclear) nuclear matter was introduced. The experimental characterization of cold bulk nuclear matter began by setting the surface, symmetry, and Coulomb terms of the liquid drop expression to zero, retaining only the volume term. This, together with the independent measurement of nuclear radii (inferable from the surface and Coulomb coefficients), defined the fundamental properties of cold bulk nuclear matter, namely its binding energy and density at saturation.

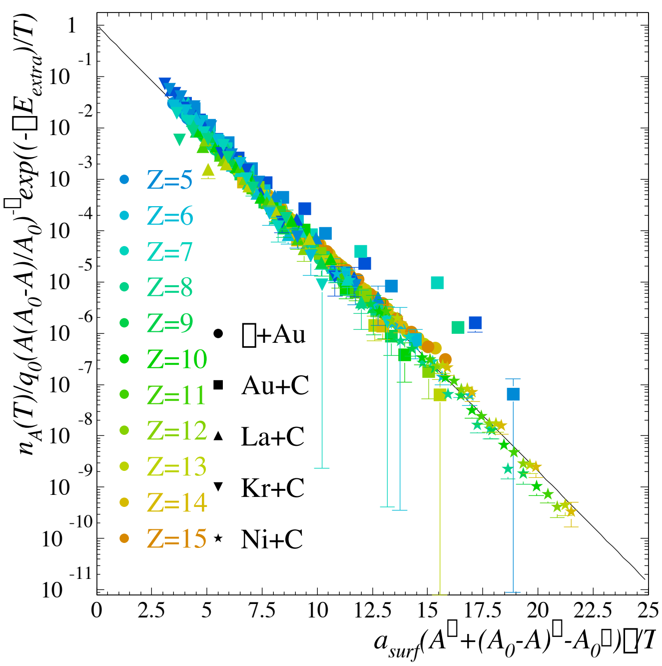


FIG. 1: The scaled fragment yields fall on a single line.

The concept of the bulk nuclear liquid leads naturally to a nuclear vapor, evidence of which came from the observation of neutron evaporation. The characterization of the properties bulk nuclear matter, such as its phase diagram and equation of state is one of the most eminent goal of nuclear physics. Here we present a study of fragment yields from five different reactions and three different experiments: the π+Au experiment performed by the ISiS collaboration at the BNL AGS; the Au+C, La+C and Kr+C experiments performed by the EOS collaboration at the LBNL Bevalac; and the Ni+C experiment performed at the LBNL 88" Cyclotron.

The fragment yields were fit with a modified form of Fisher's droplet model [1]. Fisher's model describes the condensation of clusters in a vapor and describes a variety of clustering systems [2]. Fisher's model gives the concetration of clusters with $A$ constituents at temperature $T$ as $n_A \propto \exp(-\Delta G/T)$ where $\Delta G$ is the free energy cost of droplet, or cluster, or fragment formation. To fit the nuclear fragment yields the $\Delta G$ in Fisher's model was modified to take into account of the finite size of the nuclei in question and their nuclear characteristic, e.g. charge and isospin.

To account for the finite size of the nuclei $\Delta G$ depends on not only the fragment in question ($A$,$Z$), but the initial nucleus from which it came ($A_0$,$Z_0$) and the fragment's complementary nucleus. Thus $\Delta G = G(A,Z,T) + G(A_0 - A, Z_0 - Z, T) - G(A_0, Z_0, T)$, in the bulk limit ($A_0 \to \infty$, neutral, symmetric matter) the complement and initial nucleus contributions cancel leaving only the fragment's contribution as in Fisher's original formulation. Here $G(A,Z,T) = E(A,Z) - TS(A,S)$; $E(A,Z)$ is the binding energy of the nucleus in question plus any energy due to angular momentum $E(A,Z) = a_{\mathrm{vol}} + a_{\mathrm{surf}}A^{2/3} + a_{\mathrm{Coul}}Z^2/A^{1/3} + a_{\mathrm{sym}}(A - 2Z)^2/A + E_L$; the Coulomb interaction energy also contributes to the energy of fragment and its complement; $S(A) = \ln(A^{-\tau}\exp(a_{\mathrm{surf}}A^{\sigma}/T_c))$ with $\tau \approx 2.2$ and $\sigma \approx 2/3$ and $T_c$ the critical temperature [1, 2]. The combination of the surface energy and surface entropy gives rise to the term $a_{\mathrm{surf}}(A^{\sigma} + (A_0 - A)^{\sigma} - A_0^{\sigma})\varepsilon$, seperating this term from $\Delta G$ leaves a quantity labeled $\Delta E_{\mathrm{extra}}$. Fitting the nuclear fragment yields from all reactions to Fisher's model using this $\Delta G$ and leaving $T_c$ as a fit parameter produces the scaling showing in Fig. 1 and gives $T_c = 18.5 \pm 1.6$MeV.

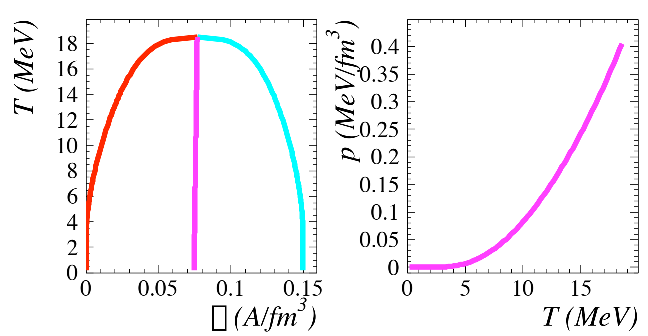


FIG. 2: The phase diagram of bulk nuclear matter.

Using the resulting $T_c$ and the techniques in references [3, 4] the phase diagram of bulk nuclear matter (shown in Fig.2) can be produced. The critical density is $\rho_c \approx 0.08A/\mathrm{fm}^3$ and the critical density is $p_c \approx 0.4$ Mev/fm$^3$.

[1] M. E. Fisher, Physics **3**, 255 (1967).
[2] C. M. Mader *et al*, Phys, Rev, C **68**, 064601 (2003).
[3] J. B. Elliott *et al.*, Phys. Rev. Lett. **88**, 042701 (2002).
[4] J. B. Elliott *et al.*, Phys. Rev. C **67**, 024609 (2003) .